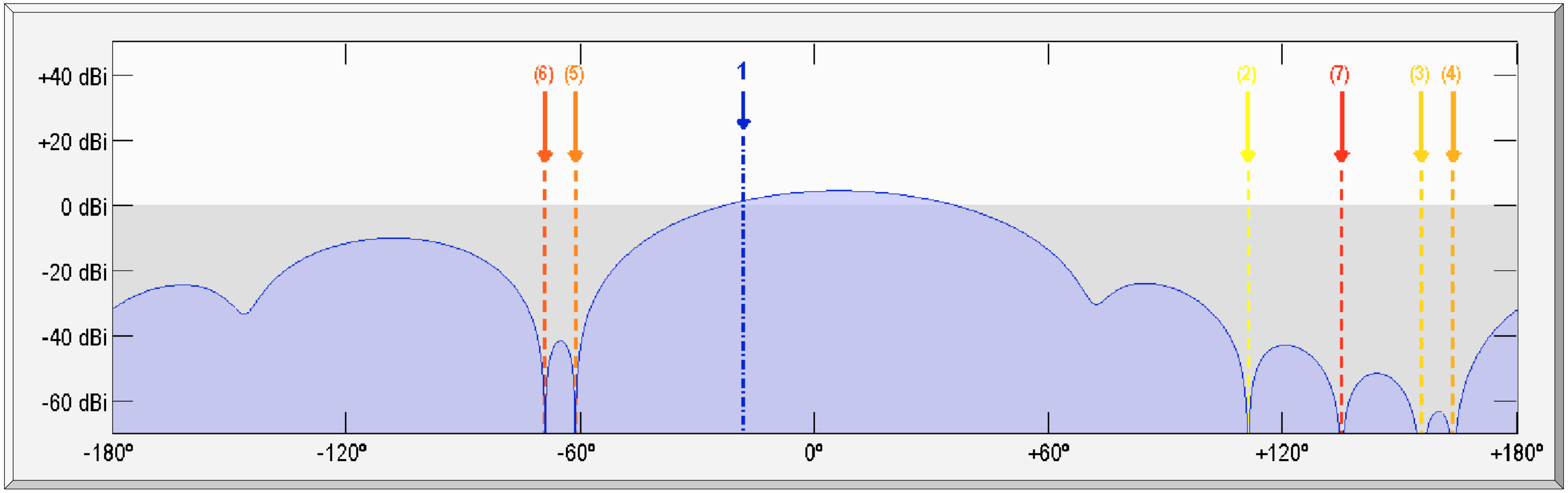
Excision of Interference in Communication and Analysis Systems



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Scope of Tutorial

- Review basic foundation & methods for interference excision
  - What it is
  - Similarities and differences with other adaptation goals
    - » Matched filter, maximal-ratio despreading/detection
    - » Equalization
    - » Signal separation
    - » Externals estimation (DF, geolocation, parameter estimation, etc.)
  - Fundamental capabilities and limitations
  - Key system engineering constraints
- Focus on *linear* excision of *additive* interference in this tutorial
  - Computationally most feasible
    - » Least costly as well in many cases
  - Algorithmically most accessible and predictable
  - Biggest "bang for the buck"
- Not intended to be an exhaustive treatment
- Linear algebra required!

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Mathematical Convention for Scalars, Vectors, and Matrices

- Scalars *italicized*, except when referring to elements of vectors or matrices
- Vectors lower-case, **boldfaced**; always column vectors unless explicitly transposed:

$$\mathbf{v} = \begin{pmatrix} (\mathbf{v})_1 \\ \vdots \\ (\mathbf{v})_K \end{pmatrix}$$

- Matrices UPPER-CASE, **boldfaced**:

$$\mathbf{M} = \begin{pmatrix} (\mathbf{M})_{1,1} & \cdots & (\mathbf{M})_{1,L} \\ \vdots & \ddots & \vdots \\ (\mathbf{M})_{K,1} & \cdots & (\mathbf{M})_{K,L} \end{pmatrix}$$

- Hermitian (conjugate-transpose) operation $(\bullet)^H = \left((\bullet)^T\right)^*$ used throughout with complex entities:

$$\mathbf{v}^H = \begin{bmatrix} (\mathbf{v})_1^* & \cdots & (\mathbf{v})_K^* \end{bmatrix}, \quad (x + jy)^* = x - jy$$

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Mathematical Convention for Data Series

- Internal Hermitian operation used to convert vector data series to matrix format:

$$\mathbf{x}(n) = \begin{pmatrix} (\mathbf{x}(n))_1 \\ \vdots \\ (\mathbf{x}(n))_M \end{pmatrix}, \ n = 1,\ldots,N \quad \Leftrightarrow \quad \mathbf{X} = \begin{pmatrix} \mathbf{x}^H(1) \\ \vdots \\ \mathbf{x}^H(N) \end{pmatrix}, \ N \times M \quad \begin{cases} M = \text{degrees of freedom} \\ N \approx \text{Time-bandwidth product} \end{cases}$$

$$\Rightarrow \ \hat{\mathbf{R}}_{\mathbf{xx}} = \tfrac{1}{N}\sum_{n=1}^{N} \mathbf{x}(n)\mathbf{x}^H(n) \quad \Leftrightarrow \quad \hat{\mathbf{R}}_{\mathbf{xx}} = \tfrac{1}{N}\mathbf{X}^H\mathbf{X}, \ M \times M \text{ sample autocorrelation matrix (ACM)}$$

- Internal conjugation operation used to convert scalar data series to (column) vector format:

$$s(n) \quad n = 1,\ldots,N \quad \Leftrightarrow \quad \mathbf{s} = \begin{pmatrix} s^*(1) \\ \vdots \\ s^*(N) \end{pmatrix}, \ N \times 1$$

$$\Rightarrow \ \mathbf{x}(n) = \mathbf{i}(n) + \mathbf{a}s(n), \ n = 1,\ldots,N \quad \Leftrightarrow \quad \mathbf{X} = \mathcal{I} + \mathbf{s}\mathbf{a}^H, \ N \times M$$

- Hermitian operation typically used to perform linear combining (inner product operation):

$$y(n) = \mathbf{w}^H\mathbf{x}(n), \ n = 1,\ldots,N \quad \Leftrightarrow \quad \mathbf{y} = \mathbf{X}\mathbf{w}, \ N \times 1$$

$$\mathbf{y}(n) = \mathbf{W}^H\mathbf{x}(n), \ n = 1,\ldots,N \quad \Leftrightarrow \quad \mathbf{Y} = \mathbf{X}\mathbf{W}, \ N \times M$$

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Topics

- Description
  - What it is
  - How it is differentiated from other signal processing problems
  - General design methodology
- Capabilities
  - Motivating model — narrowband antenna array in noiseless environment
  - Extension to noisy environments
  - Extension to other linear processor structures
- Methods
  - Channel-directed versus data-directed methods
  - Specific methods
  - Implementation considerations

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Topics

- **Description**
- Capabilities
- Methods

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What is Interference Excision?

- Removal of signals *not* of interest (*SNOI's*) from one or more signals *of* interest *(SOI's)*
  - An essential attribute is that the SNOI's are undesired the system receiver, and the SOI's are desired at the system receiver
  - An additional attribute, essential for purposes of this tutorial, is that the SNOI excision can far exceed the capabilities of conventional measures (e.g., matched-filter despreaders, correlators)
- SOI's can be defined in many contexts
  - Structured information-bearing control or communication signals
  - Unstructured acoustic or electromagnetic signals (e.g., impulse noise)
  - Radar or Sonar signals
  - SOI *features* generated in signal analysis systems (sync features, geo-observables, etc.)
- SNOI's can be defined in many contexts
  - Unintentional versus intentional interference (e.g., jammers)
  - Structured versus unstructured interference
  - Co-channel versus adjacent-channel interference
  - Internetwork versus intranetwork interference
- A typical (but not essential) additional attribute is that the SNOI's are additive and independent from the SOI's (spoofers are a notable exception, not covered here)

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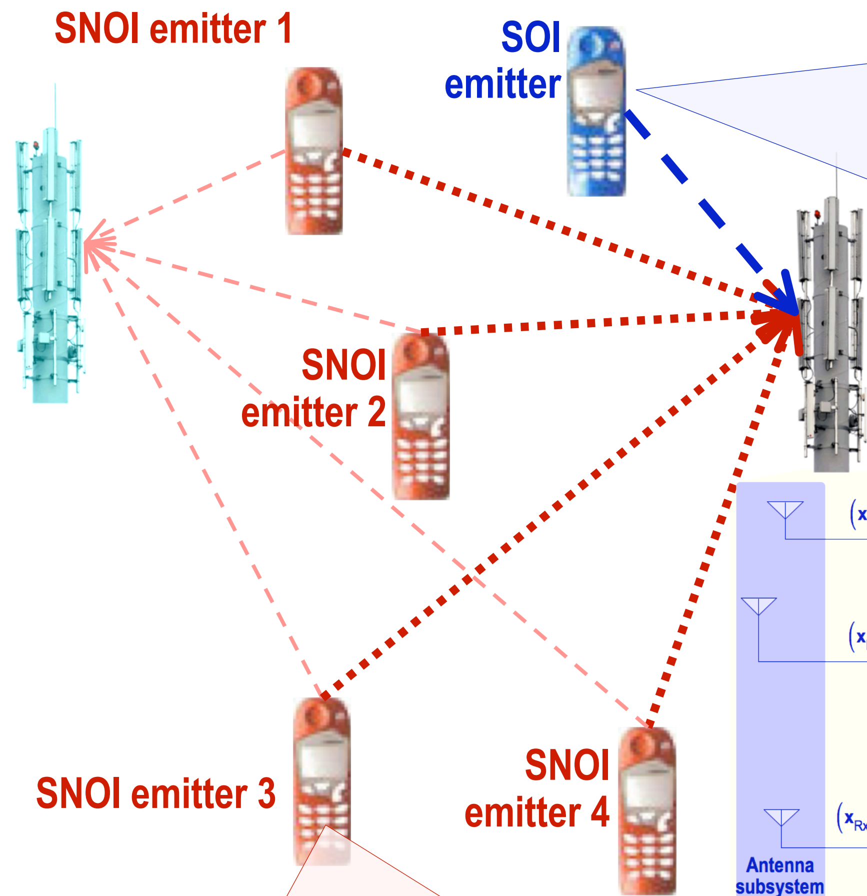
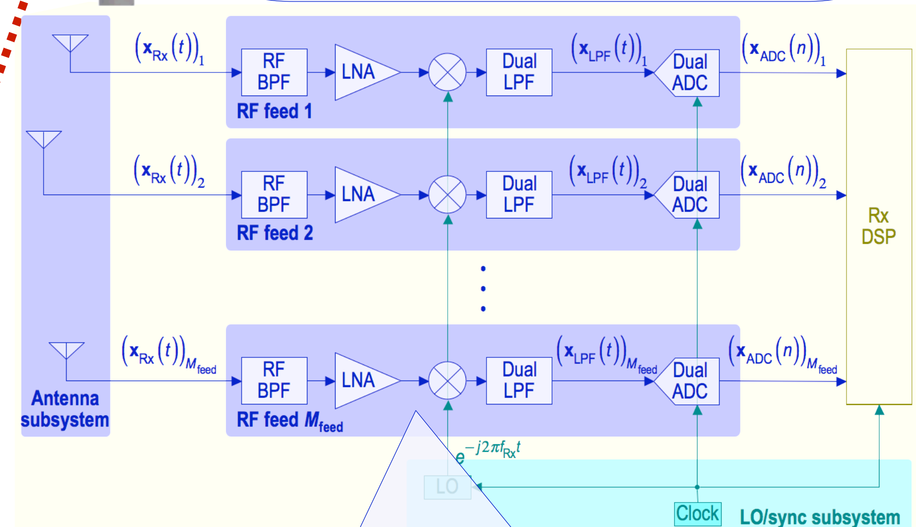
Exemplary Interference Excision Problem



Signal of Interest (SOI) to the Receiver

- Well-known signal structure, allowing SOI/SNOI discrimination
- Probable known SOI components (pilots, training symbols)
- Possible known/estimable locations, directions of arrival (DOA's)
- **Of utility to the receiver**



Signals *not* of Interest (SNOI's) to the receiver

- Unknown/partially-known signal structure
- Unknown locations, DOA's
- **Of *no* utility to the receiver**

Receiver System

- Capability to remove SNOI's

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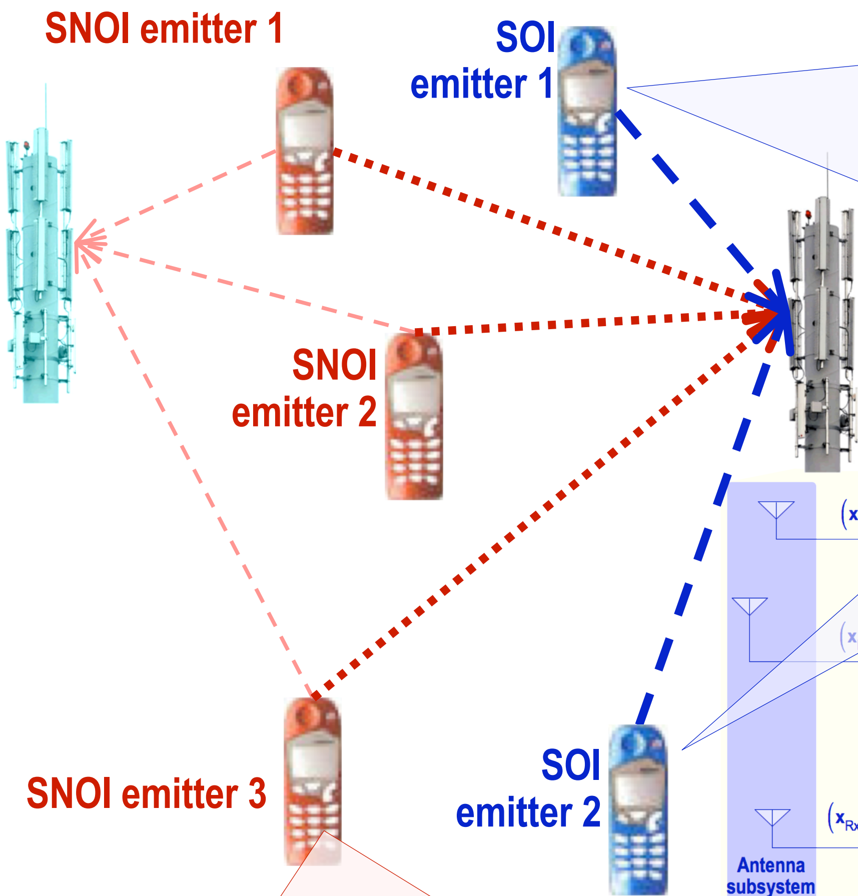
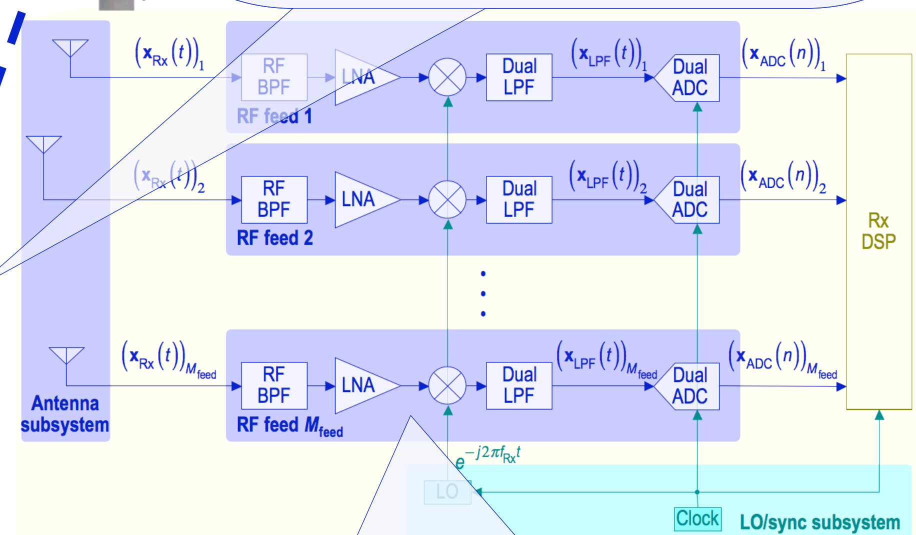
Exemplary Interference Excision Problem



Signals of Interest (SOI's) to the Receiver

- Well-known signal structure allowing SOI separation, SOI/SNOI discrimination
- Probable known and separable SOI components (pilots, training symbols)
- Possible known/estimable locations, directions of arrival (DOA's)
- **Of utility to the receiver**



Signals *not* of Interest (SNOI's) to the receiver

- Unknown/partially-known signal structure
- Unknown locations
- **Of *no* utility to the receiver**

Receiver System

- Capability to remove SNOI's
- Capability to separate SOI's

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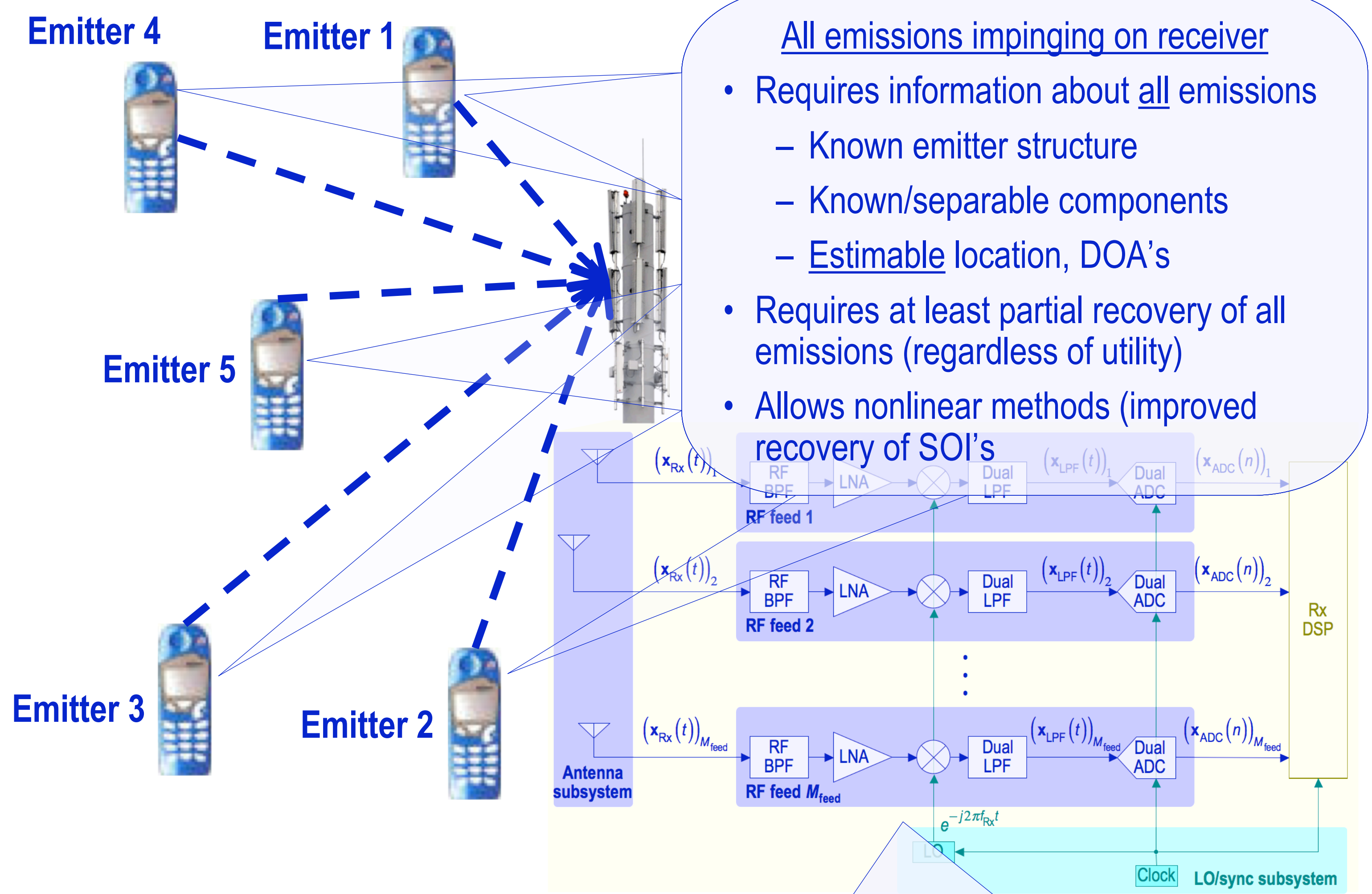
Exemplary Signal Separation Problem



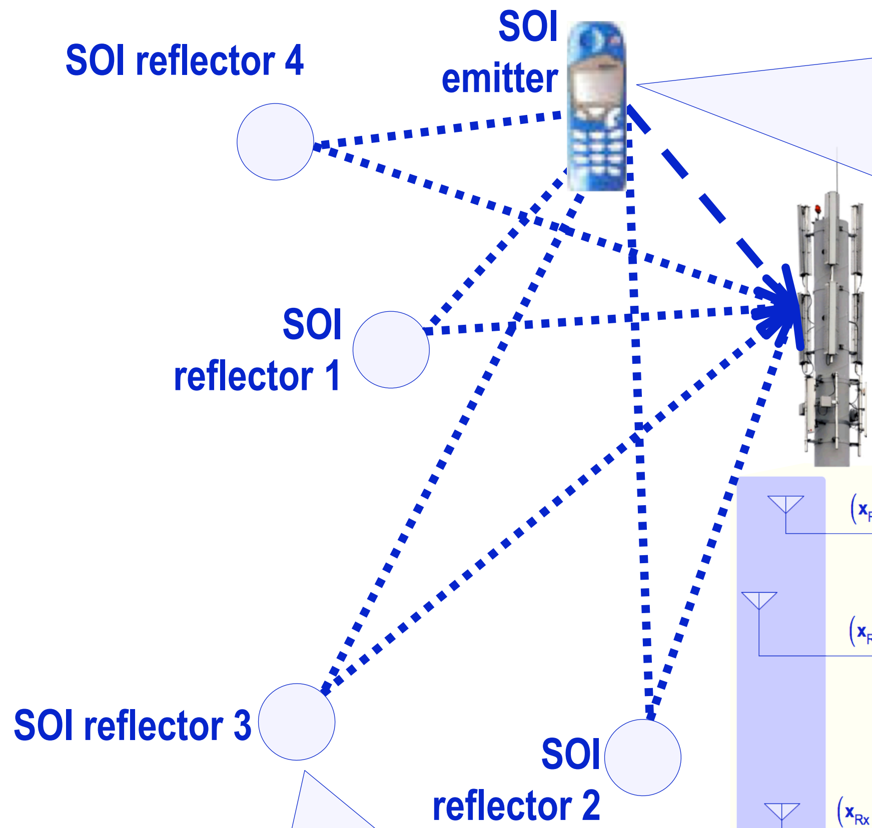
All emissions impinging on receiver

- Requires information about all emissions
  - Known emitter structure
  - Known/separable components
  - Estimable location, DOA's
- Requires at least partial recovery of all emissions (regardless of utility)
- Allows nonlinear methods (improved recovery of SOI's

Receiver System

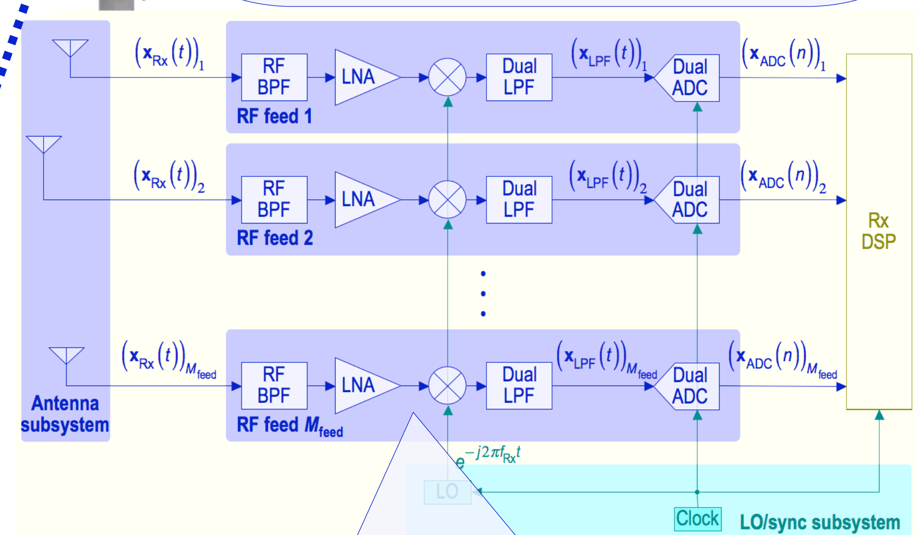
- Capability to separate all emissions

Exemplary Signal Equalization Problem



<u>Signal of Interest (SOI) to the Receiver</u>

- Well-known signal structure, allowing SOI/SNOI discrimination
- Probable known SOI components (pilots, training symbols)
- Possible known/estimable locations, directions of arrival (DOA's)
- **<u>Of utility to the receiver</u>**



<u>Reflectors or Scatterers</u>

- Correlated with emitter SOI
- **<u>Of potential utility to the receiver (diversity reception, MIMO communications)</u>**

<u>Receiver System</u>

- Capability to excise reflections
- Capability to <u>exploit</u> reflections

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Interference Excision System Design Methodology

- Identify the interference excision scenario
  - Is interference the real issue?
  - Can the problem be solved by other means (e.g., interference <u>avoidance</u>)?
  - What system/environment factors do you control?
- Develop an end-to-end model for the interference excision problem
  - SOI and SNOI transmit signal models (if appropriate)
  - SOI-to-receiver and SNOI-to-receiver channel model(s)
    - » General model
    - » Learnable parameters
    - » Probable deviations
  - Expected receiver system/network impairments
- Develop a receiver system/network structure that <u>can</u> excise the interference
  - Prove if possible through analysis and simulations using ground truth data
- Develop an <u>effective</u> adaptation algorithm
  - <u>Can</u> adapt the receiver structure to achieve the desired excision
  - <u>Robust</u> to model deviations
  - <u>Cost effective</u>
- Adjust controllable factors as needed/possible to maximize utility (cost or effectiveness)

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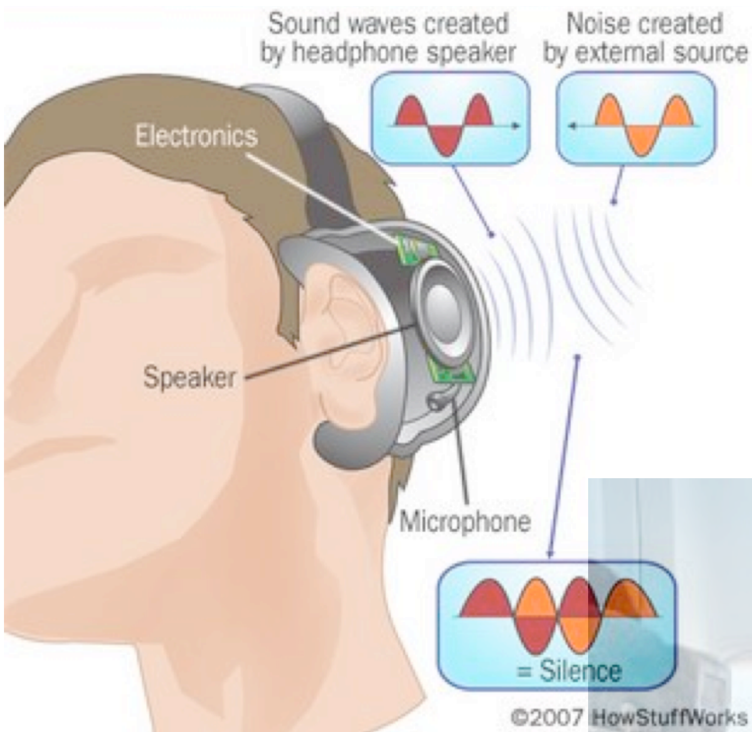
Example: Adaptive Noise Canceller*



- Forty years old
- Early applications:
  - Electrocardiography (fetal heart monitoring)
  - Adaptive sidelobe cancellation in antenna arrays
  - Telephone echo cancellation
  - Line detection, estimation in antisubmarine warfare

* B. Widrow, J. McCool, J. Kaunitz, J. Williams, C. Hearn, R. Ziedler, E. Dong, R. Goodlin, "Adaptive Noise Cancelling: Principles and Applications," *Proc. IEEE*, Vol. 63, No. 12, pp. 1692-1716, Dec. 1975

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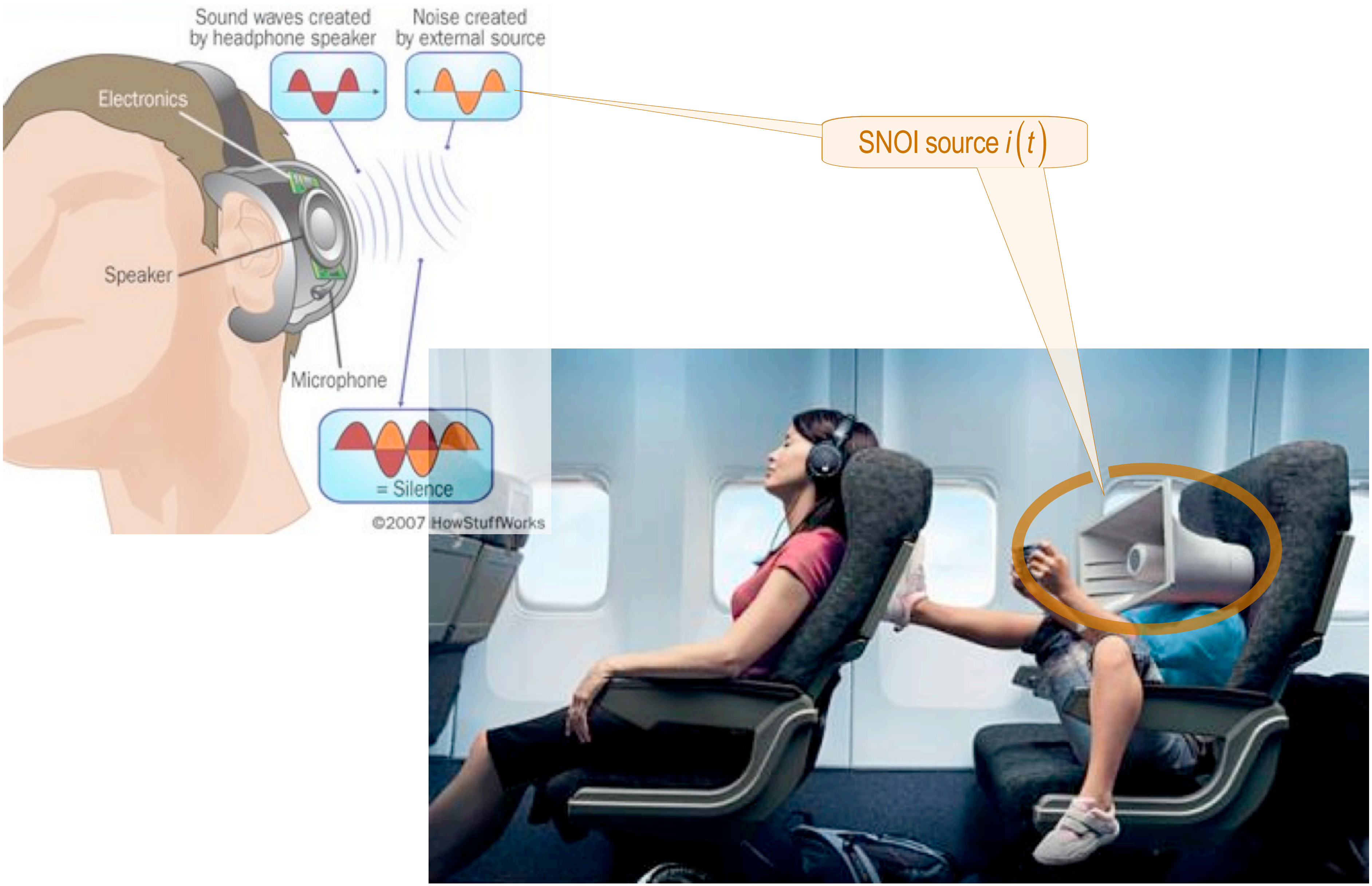
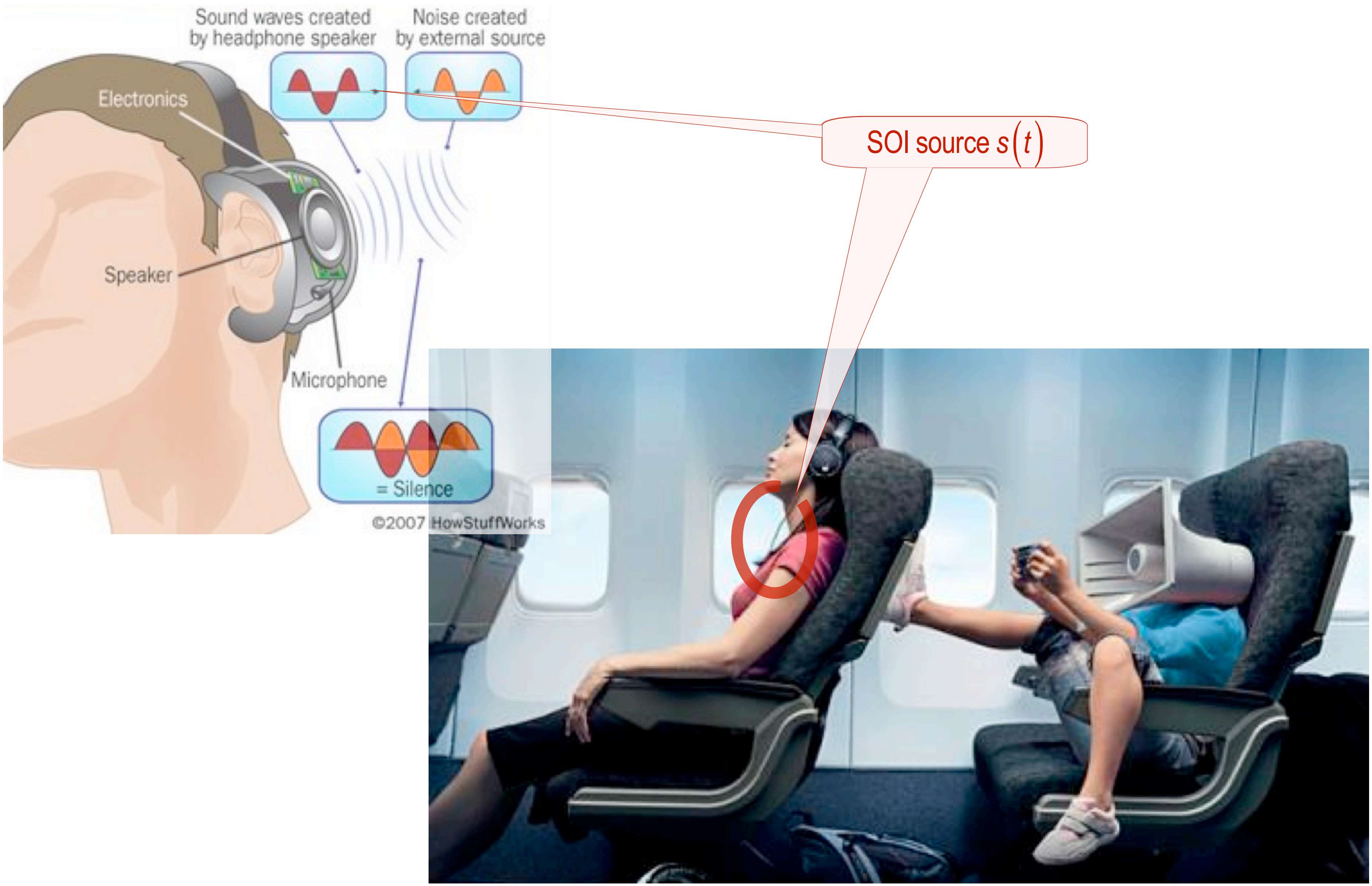
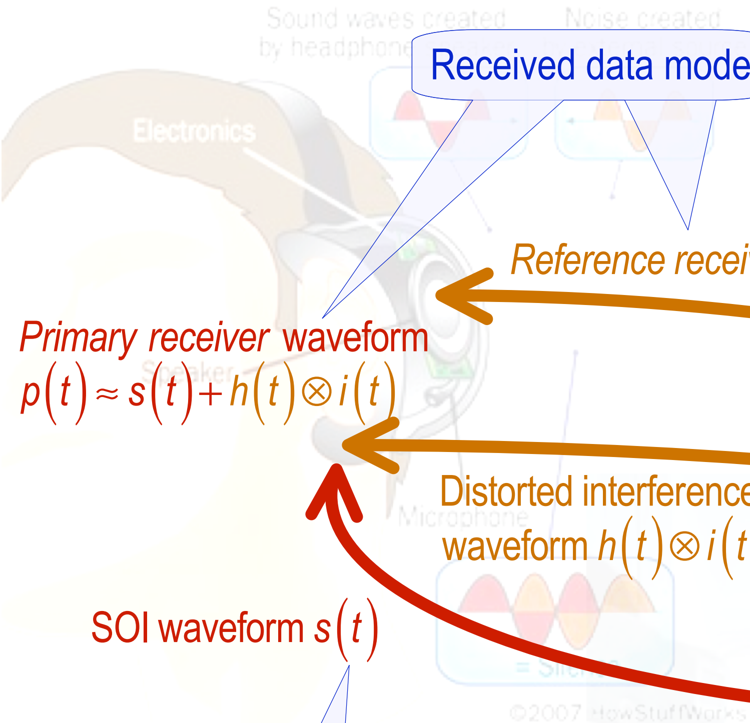
Example: Adaptive Noise Canceller

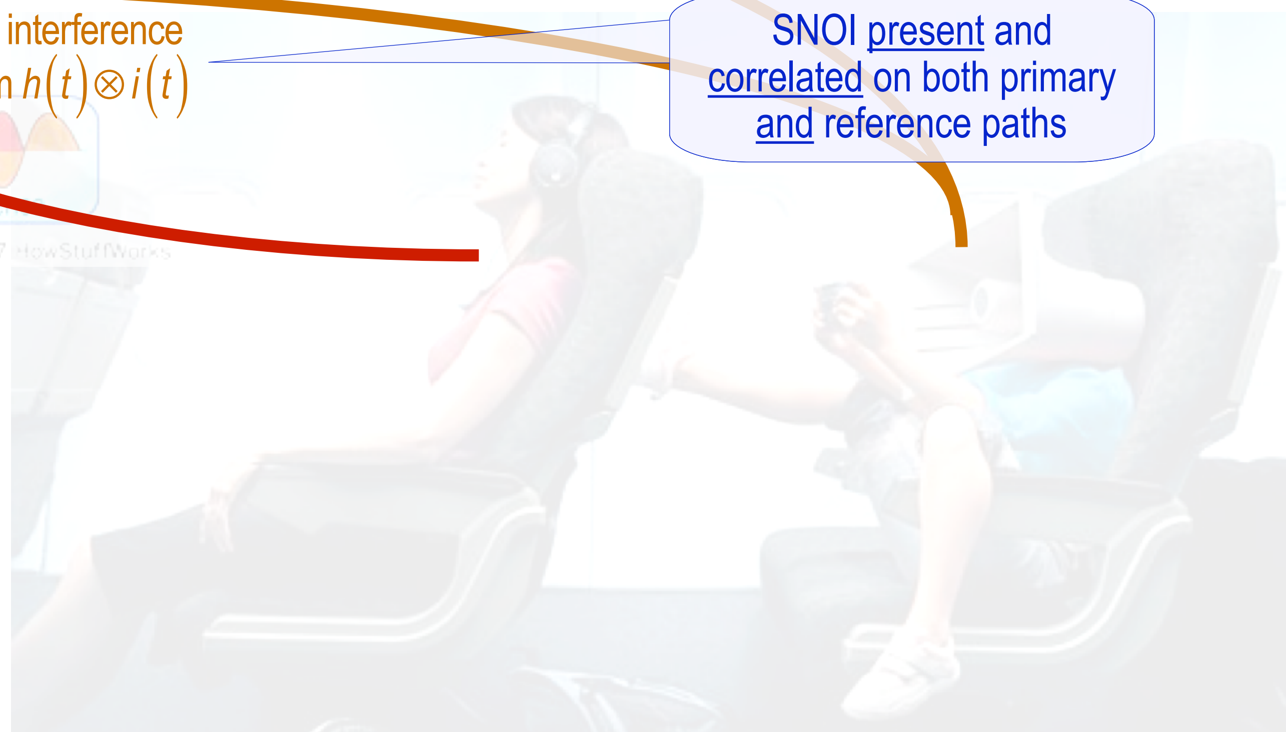


Example: Adaptive Noise Canceller



Example: Adaptive Noise Canceller





Received data model

Reference receiver waveform $r(t) \approx i(t)$

Primary receiver waveform
$p(t) \approx s(t) + h(t) \otimes i(t)$

Distorted interference
waveform $h(t) \otimes i(t)$

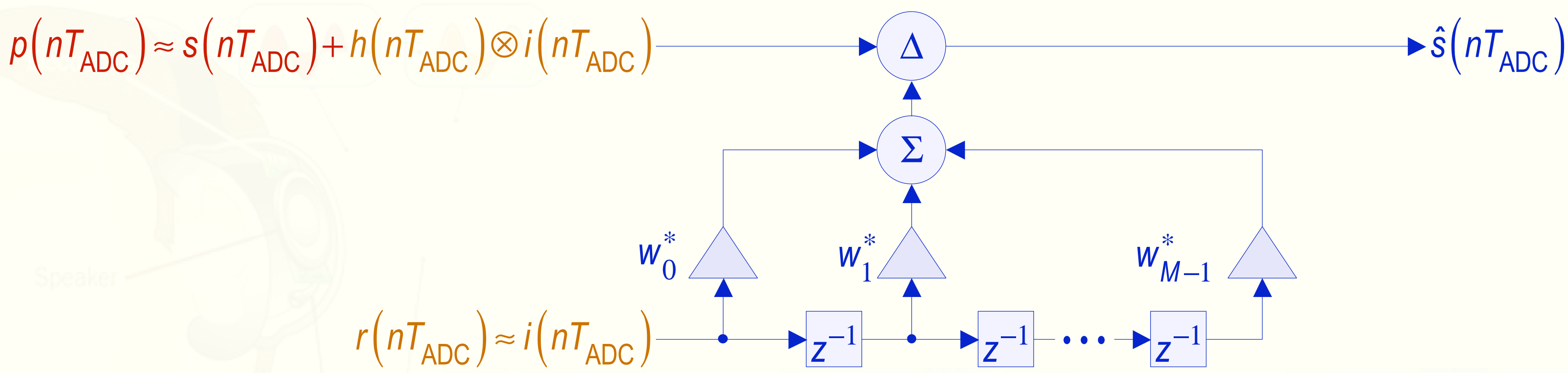
SOI waveform $s(t)$

SNOI present and correlated on both primary and reference paths

SOI present only on primary path

Example: Adaptive Noise Canceller

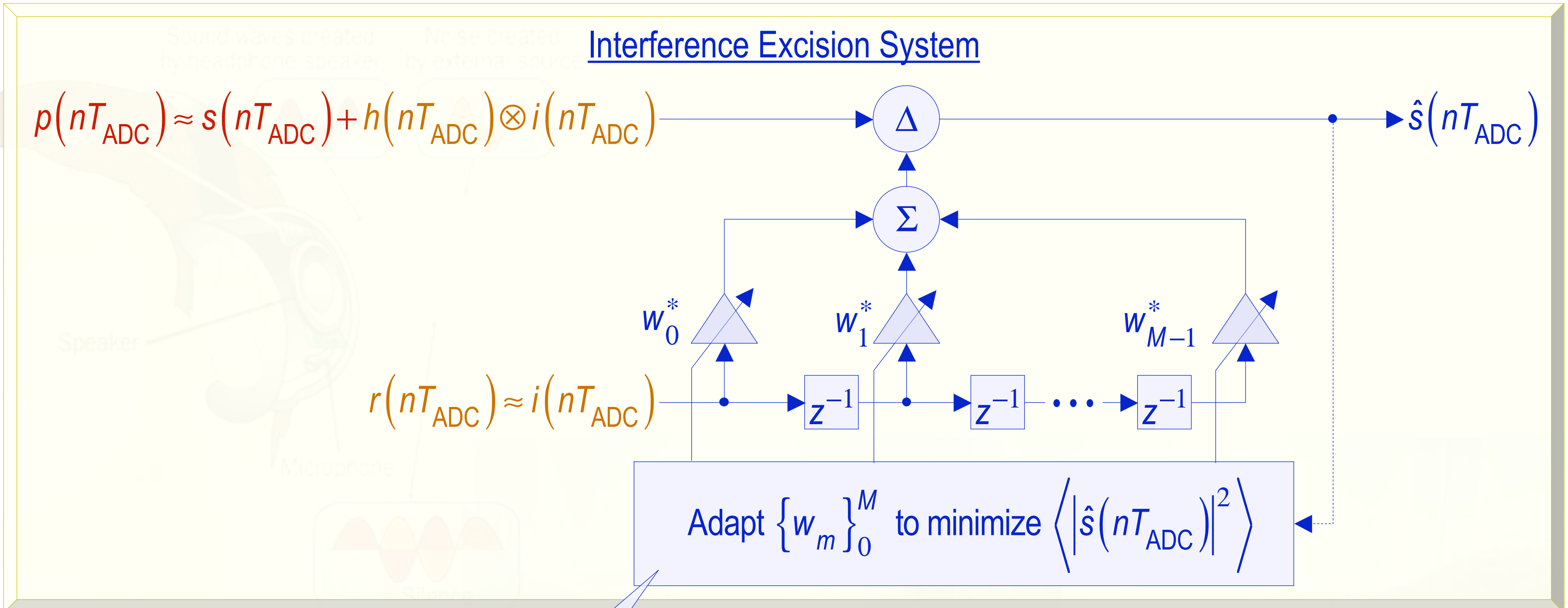
Interference Excision System Structure



$$\{w_m^*\} \rightarrow \{h(mT_{\mathrm{ADC}})\} \Rightarrow \hat{s}(nT_{\mathrm{ADC}}) \rightarrow s(nT_{\mathrm{ADC}})$$

Motivating rationale for structure

Example: Adaptive Noise Canceller



Adaptation criterion

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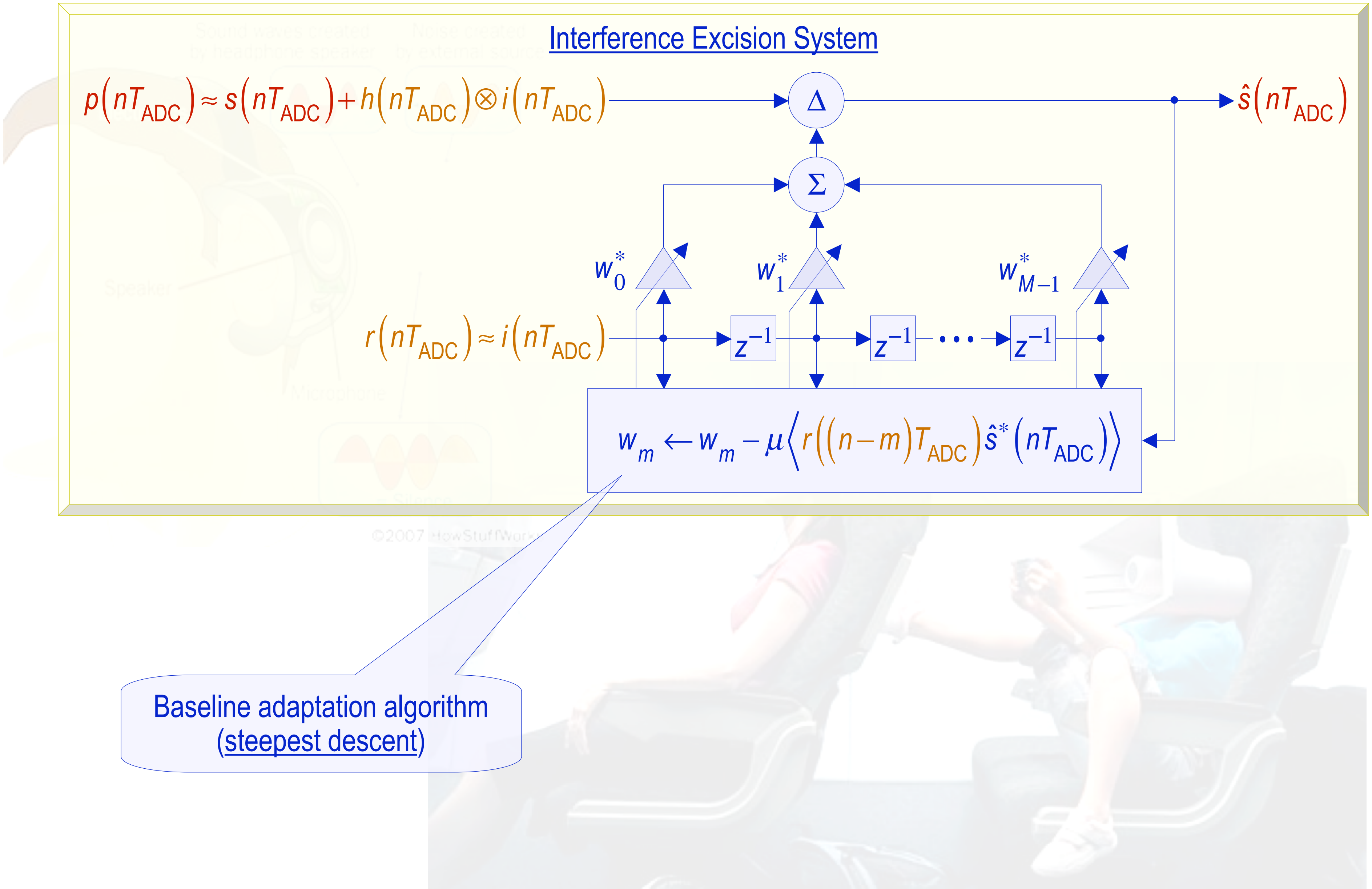
Example: Adaptive Noise Canceller



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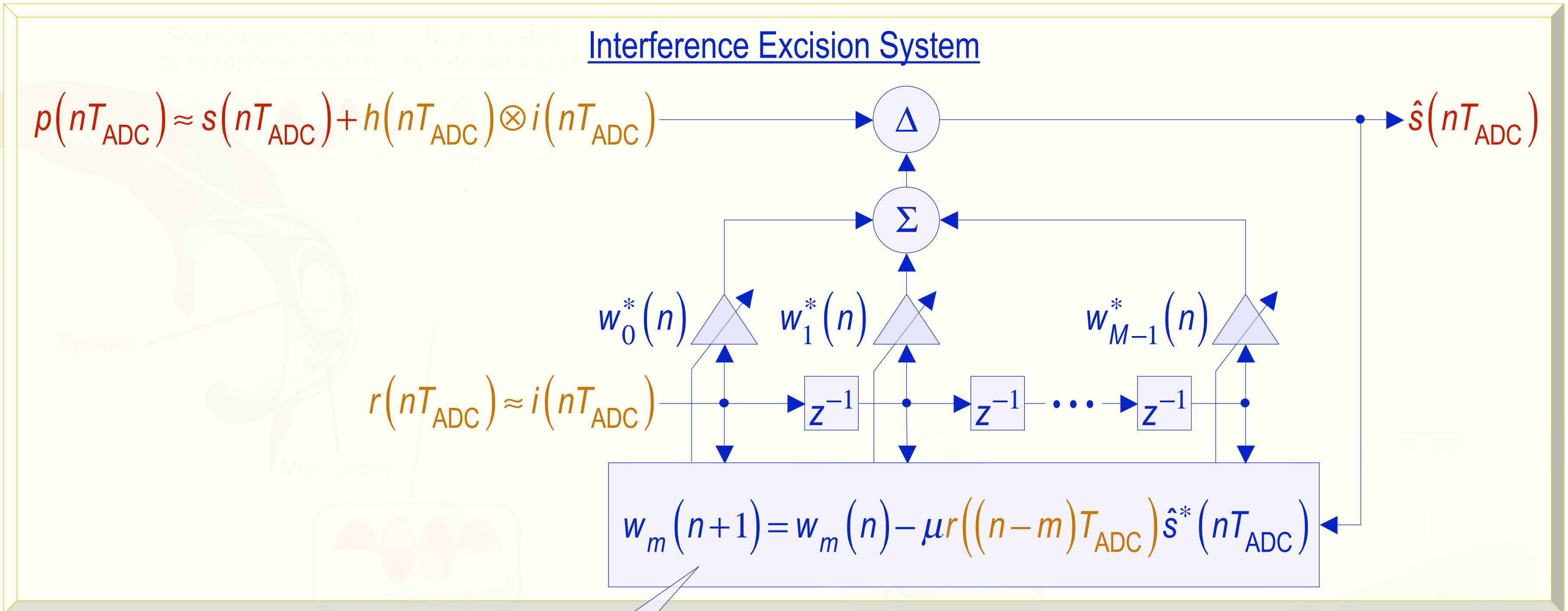

Implemented adaptation algorithm
(Widrow-Hoff LMS Algorithm, 1960)

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Adaptive Noise Canceller Pitfalls

- Is the reference path truly SOI free?
  - Well-known reference leakage problem
  - Causes cancellation of SOI as well as SNOI
- Is the interference the same in reference and primary paths?
  - NO: independent receiver noise will always be injected into each path
  - Causes incomplete removal of interference
- Can an FIR canceller completely remove the interference?
  - NO: independent receiver noise will always be present on each path
  - Distortion model between interference received on primary and reference paths may not be well modelled by canceller filter
    - » May be longer than canceller filter
    - » May be noncausal (arrives at primary ahead of reference)
    - » May be better modeled as AR (distortion on reference path) or ARMA (distortion on both)
    - » May be time-varying (non-LTI)
    - » May be from multiple SNOI's (overloaded array)
  - Results in incomplete removal of interference
- Will the adaptation algorithm adapt quickly enough (eigenvalue spread problem)?
- Is the solution cost effective? Is the solution necessary?
  - Is the improvement dramatic enough relative to other solutions?
  - Will the customer buy it?